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Assessment of lake sensitivity to acidic deposition in national parks of the Rocky Mountains

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Abstract. The sensitivity of high-elevation lakes to acidic deposition was evaluated in five national parks of the Rocky Mountains based on statistical relations between lake acid-neutralizing capacity concentrations and basin characteristics. Acid-neutralizing capacity (ANC) of 151 lakes sampled during synoptic surveys and basin-characteristic information derived from geographic information system (GIS) data sets were used to calibrate the statistical models. The explanatory basin variables that were considered included topographic parameters, bedrock type, and vegetation type. A logistic regression model was developed, and modeling results were cross-validated through lake sampling during fall 2004 at 58 lakes. The model was applied to lake basins greater than 1 ha in area in Glacier National Park ($n = 244$ lakes), Grand Teton National Park ($n = 106$ lakes), Great Sand Dunes National Park and Preserve ($n = 11$ lakes), Rocky Mountain National Park ($n = 114$ lakes), and Yellowstone National Park ($n = 294$ lakes). Lakes that had a high probability of having an ANC concentration <100 μeq/L, and therefore sensitive to acidic deposition, are located in basins with elevations >3000 m, with $<30\%$ of the catchment having northeast aspect and with $>80\%$ of the catchment bedrock having low buffering capacity. The modeling results indicate that the most sensitive lakes are located in Rocky Mountain National Park and Grand Teton National Park. This technique for evaluating the lake sensitivity to acidic deposition is useful for designing long-term monitoring plans and is potentially transferable to other remote mountain areas of the United States and the world.

Key words: acidic solutes; alpine; atmospheric deposition; GIS; lake chemistry; monitoring; Rocky Mountains, USA; U.S. national parks.

Introduction

Population growth, water use, and energy development in the western United States are affecting natural resources and environments (Baron 2002). Alpine and subalpine ecosystems are particularly vulnerable to natural and human-induced stressors (Williams et al. 2002). Physical characteristics of high-elevation basins, such as steep topography, thin, rocky soils, and sparse vegetation, and a short growing season make lakes particularly susceptible to contaminant inputs from atmospheric deposition (Turk and Spahr 1991). Throughout the Rocky Mountain region, energy generation, transportation, industry, and agriculture, produce emissions of SO_2, NO_x, and NH_3 that may contribute to acidification and eutrophication of alpine and subalpine lakes. Atmospheric deposition of dissolved inorganic nitrogen (DIN = nitrate [NO_3] + ammonium [NH_4]) to high-elevation lakes has the potential to change the nutrient balance of aquatic ecosystems, increasing the possibility of episodic acidification and change in nutrient status (Williams et al. 1996, Baron 2006).

Limited data on water-quality data are available for high-elevation lakes in many national parks of the Rocky Mountains (Clow et al. 2002, Woods and Corbin 2003*a*, *b*, Corbin et al. 2006). Monitoring of surface waters is needed in national parks of the Rocky Mountain region to assess current conditions of aquatic ecosystems, and to evaluate the long-term effects of atmospheric deposition of contaminants on these aquatic ecosystems. These environments are often remote, however, and it can be expensive and logistically difficult to monitor long-term changes in the chemical and biological composition of these lakes.

In the Rocky Mountains, there is concern that lakes with acid-neutralizing capacity (ANC) concentrations less than 100 μeq/L are particularly sensitive to atmospheric inputs of acidity (Williams and Tonnessen 2000). ANC is a measure of the water's capacity to buffer acidic inputs and a measure of the concentration of solutes. Previous studies have documented the relation between basin characteristics and ANC concentrations in surface waters of mountain lakes in the western United States (Melack et al. 1985, Clow and

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Sueker 2000, Rutkowski et al. 2001, Sueker et al. 2001, Berg et al. 2005, Nanus et al. 2005, Corbin et al. 2006). Lake elevation was found to be a predictor of surface-water ANC concentrations in two Colorado Wilderness Areas (Turk and Adams 1983, Turk and Campbell 1987), Yellowstone and Grand Teton National Parks (Nanus et al. 2005), and in the Swiss Alps (Drever and Zorbrist 1992). Clow and Sueker (2000) found that slope steepness was negatively correlated with lake ANC concentrations in Rocky Mountain National Park and attributed this to fast hydrologic flushing rates on steep slopes with poorly developed soils and limited vegetative cover. Rutkowski et al. (2001) found that bedrock geology and elevation were significant predictors of ANC in surface waters in wilderness areas of Nevada, Idaho, Utah, and Wyoming. Bedrock geology was a strong predictor of ANC in the Sierra Nevada (Melack et al. 1985), Rocky Mountain National Park (Clow and Sueker 2000), and in Grand Teton National Park (Corbin et al. 2006). The presence of carbonate lithology in a basin can be very effective in neutralizing acidity in high-elevation basins and generally results in elevated concentrations of ANC (Berg et al. 2005). Berg et al. (2005) found that the ratio of lake perimeter to lake area was significantly related to ANC concentration, such that higher ratios resulted in higher lake ANC.

Results of the previous studies indicate that it is possible to develop statistical models that use basin characteristics as explanatory variables to predict ANC concentrations in alpine and subalpine lakes. Clow and Sueker (2000) predicted ANC concentrations in Rocky Mountain National Park using multiple linear regression and found that predicted ANC concentrations vs. actual yielded an r^2 of 0.92. However, when predicted values were compared with 1985 Western Lake Survey data less than 35% of the variance was explained (Clow and Sueker 2000). Berg et al. (2005) found that the general linear models used to predict discrete ANC concentration in unsampled high-elevation lakes of the Sierra Nevada explained 51% of the variation in observed ANC, with the majority of predicted lake ANCs greater than measured ANC.

To minimize the costs and resources associated with designing and implementing regional water-quality monitoring programs in high-elevation environments, a scientific approach to identify the most sensitive lakes without sampling each one is needed. The combined use of multivariate logistic regression and GIS modeling holds promise. This approach has been used in a number of water-quality investigations at subregional and regional scales to predict groundwater vulnerability to contaminants (Teso et al. 1996, Nolan 2001, Battaglin et al. 2003, Rupert 2003). The primary advantage of logistic regression over multiple linear regression and general linear models is that the binary response can be established using a meaningful threshold, such as a targeted background concentration or laboratory detection level. The results of a logistic regression model are expressed in probability units of the predicted dependent variable in reference to the specified threshold (such as below an ANC threshold), rather than expressed as a predicted discrete value of ANC concentration, such as determined using linear regression. Because the model results are expressed in probability units, resource managers can develop monitoring programs based on any particular level of acceptable resource management risk. Successful application of the GIS modeling and multivariate logistic regression approach was demonstrated for alpine and subalpine lakes in Grand Teton National Park and Yellowstone National Park (Nanus et al. 2005); however, an assessment of lake sensitivity to deposition across the broader Rocky Mountain region has not been conducted.

In 2004, the U.S. Geological Survey, in cooperation with the National Park Service, began a study to evaluate the sensitivity of alpine and subalpine lakes in national parks of the Rocky Mountains to atmospheric deposition of contaminants, based on statistical relations between water-quality and landscape attributes that are quantified by GIS. A Rocky Mountain regional model was developed to evaluate regional lake sensitivity and for inter-park comparison. For cross-validation of the regional model, 58 randomly selected lakes from all five parks were sampled during late summer through early fall 2004. The approach developed in this study for identifying deposition-sensitive lakes in remote areas that may need to be monitored could be used as a framework for application to other high-elevation environments of the western U.S. and the world.

Study area

Five national parks in the Rocky Mountains were studied: Glacier National Park (Glacier), Montana; Grand Teton National Park (Grand Teton), Wyoming; Great Sand Dunes National Park and Preserve (Great Sand Dunes), Colorado; Rocky Mountain National Park (Rocky Mountain), Colorado; and Yellowstone National Park (Yellowstone), Wyoming. Four of the five parks are located along the Continental Divide (Table 1, Fig. 1) and have a large number of alpine and subalpine lakes, ranging in elevation from less than 1000 m in Glacier to more than 3500 m in Rocky Mountain (Table 2). These national parks are in glaciated mountain terrain (Madole 1976, Richmond and Fullerton 1986). Dominant bedrock types for each park are as follows: sedimentary rocks in Glacier (U.S. Geological Survey 1992*b*), granitic rocks in Grand Teton (U.S. Geological Survey 1992*a*) and Rocky Mountain (U.S. Geological Survey 1990), volcanic rocks in Yellowstone (U.S. Geological Survey 1988), and granitic and sedimentary rocks in Great Sand Dunes (National Park Service 2004). Average annual precipitation amounts in the Rocky Mountains increase as a function of elevation and latitude, mountainous areas above 3000 m elevation generally receive at least 800 mm precipitation per year,

TABLE 1. National Parks in the Rocky Mountain region and their characteristics.

Characteristic	Glacier	Yellowstone	Grand Teton	Rocky Mountain	Great Sand Dunes
Area (km^2)	4101	8980	1256	1078	343
Maximum elevation (m)	3190	3122	4198	4346	4317
Number of lakes	244	294	106	114	11
Dominant bedrock types	sedimentary	volcanic	granite	granite	granite and sedimentary

most of which accumulates in a seasonal snowpack (Spatial Climate Analysis Service 2000).

Many of the lakes used in model calibration and validation are located in alpine and subalpine terrain where soils are poorly developed, vegetation is sparse, and growing seasons are short. The lake selection process included a random selection component similar to the Western Lake Survey (Kanciruk et al. 1987, Landers et al. 1987, Silverstein et al. 1987), to allow extrapolation of the results to a broad population of lakes. Lakes with a surface area greater than 1 ha were used to avoid inclusion of small tarns and ponds in calibration and validation data sets. Model results were then applied to all lakes greater than 1 ha in area, 769 lakes in the five parks included in this study.

METHODS

Description of data used in the statistical models

ANC concentrations for 151 alpine and subalpine lakes from the five national parks were used to calibrate the logistic regression models. We focused on base flow conditions when ANC concentrations are relatively consistent over time; therefore, only available data from lakes that were sampled during late summer through early fall were included. Few data were available for Yellowstone (Woods and Corbin 2003*b*), Glacier (Landers et al. 1987), and Great Sand Dunes (F. Bunch, *personal communication*). More extensive water-quality information exists for alpine and subalpine lakes in Rocky Mountain (Clow et al. 2002) and Grand Teton (Gulley and Parker 1985, Landers et al. 1987, Woods and Corbin 2003*a*, Corbin et al. 2006; K. A. Tonnessen and M. W. Williams, *personal observation*), than for the other three parks in this study. Chemical concentrations in high-elevation lakes in these five parks were sampled in 1985, and then again in 1999, and it was determined that the only national park with significant changes in base flow ANC concentrations was Rocky Mountain (Clow et al. 2003). For Rocky Mountain, ANC concentrations were not variable across the concentration thresholds used for this study. These results indicate that data collected at the five parks may be combined for sites with multiple years of ANC concentration data from one data set or multiple data sets.

Lakes were sampled during late summer through early fall 2004 in all five parks for cross-validation of the statistical models. Samples were collected at 58 randomly selected high-elevation lakes that are spatially distributed within each of the national parks (Nanus et al. 2005). Lake samples were filtered (0.45 μm) and collected at the lake outlets and chemical concentrations were analyzed following standard procedures at the Kiowa Environmental Chemistry Laboratory, Boulder, Colorado (Seibold 2001), which specializes in analysis of extremely dilute waters such as those found in the study area.

Physical characteristics that were tested in the statistical model for correlation with ANC concentrations included elevation, slope, aspect, and bedrock geology. Boundaries for the watershed of each lake were delineated using a 10-m digital elevation model (DEM; U.S. Geological Survey 2000*a*, *b*). To evaluate the effect of error associated with basin delineation on the model, basin boundaries using multiple methods, including manual and automated in GIS, were compared and the difference in model outputs were calculated at less than 5%.

For each lake basin, the 10-m DEM was used to calculate mean elevation, slope, basin area, lake/basin area, percentage of steep slopes (slopes >30°), and percentage of aspect (by 45° increments). Additional basin characteristics that were derived from National Park Service GIS data include watershed area, lake area, ratio of lake area to watershed area, ratio of lake

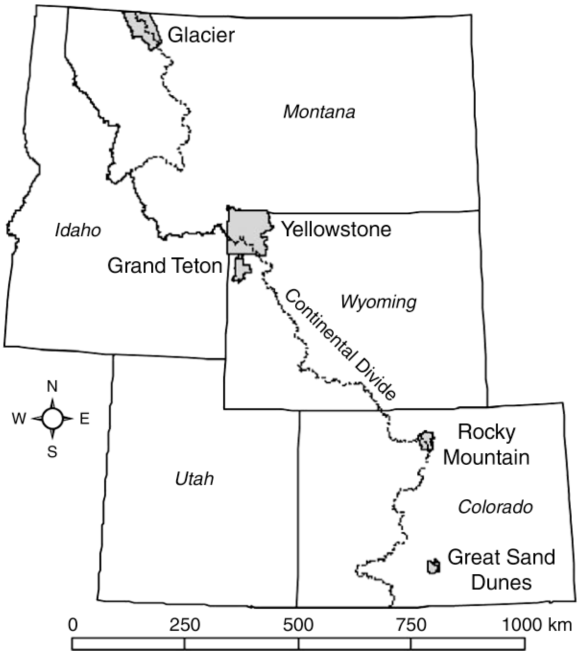

FIG. 1. Location of National Parks included in this study.

TABLE 2. Select physical and chemical characteristics of lakes used in regional model development.

Measure	ANC† (μeq/L)	Lake elevation (m)	Bedrock geology with low buffering capacity (%)	Northeast aspect (%)
Glacier (*n* = 33 lakes)				
Minimum	39	956	0	0
First quartile	326	1500	8	11
Median	853	1692	35	14
Third quartile	1111	1826	67	18
Maximum	1550	2605	100	35
Yellowstone (*n* = 23 lakes)				
Minimum	54	1953	0	4
First quartile	170	2200	0	10
Median	320	2322	0	17
Third quartile	702	2394	6	25
Maximum	1621	2674	25	33
Grand Teton (*n* = 52 lakes)				
Minimum	18	2035	0	0
First quartile	69	2104	70	12
Median	108	2805	89	18
Third quartile	270	2958	100	23
Maximum	1600	3247	100	49
Rocky Mountain (*n* = 40 lakes)				
Minimum	15	1646	50	0
First quartile	44	3252	88	7
Median	55	3316	97	16
Third quartile	84	3478	100	21
Maximum	214	3625	100	37
Great Sand Dunes (*n* = 3 lakes)				
Minimum	228	3496	100	7
First quartile	294	3503	100	15
Median	361	3509	100	23
Third quartile	392	3642	100	24
Maximum	423	3774	100	24
Regional (*n* = 151 lakes)				
Minimum	15	956	0	0
First quartile	63	2070	21	11
Median	122	2715	81	16
Third quartile	583	3140	98	23
Maximum	1621	3774	100	49

† Acid-neutralizing capacity.

perimeter to lake area, percentage watershed covered by rock type (U.S. Geological Survey 1988, 1990, 1992*a*, *b*, National Park Service 2004), and percentage watershed covered by vegetation type (National Park Service 1981, 1990, 1994*b*, Rocky Mountain National Park GIS Program 1995). Errors associated with a given resolution for each basin characteristic were evaluated to determine whether data with different levels of resolution could be combined.

Bedrock lithologies were grouped into six different geochemical classes that were ranked from low to high on the basis of buffering capacity of the bedrock (Nanus et al. 2005). The geochemical rankings (GC) are as follows: GC 1, low buffering capacity, gneiss, quartzite, schist, granite; GC 2, moderate buffering capacity, andesite, dacite, diorite, phyllite; GC 3, high buffering capacity, basalt, gabbro, greywacke, argillite, undifferentiated volcanics; GC 4, very high buffering capacity, amphibolite, hornfels, paragneiss, undifferentiated metamorphic rocks; GC 5, class 5, extremely high buffering capacity, metacarbonate, marine sedimentary rocks, calc silicate and basic intrusive rocks; and GC 6, class 6, unknown buffering capacity. Vegetation type was classified into low, medium, and high classes based on the basins sensitivity to acidic deposition (Nanus et al. 2005). Basins with high sensitivity include a large percentage of snow, ice, rock, and water. Basins with medium sensitivity include forest and tundra, and those with low sensitivity include subalpine meadow. Soil type was not included in the regional model, because Great Sand Dunes did not have complete soil data, and the data that were available were not comparable across all five parks.

Atmospheric factors, including precipitation amount and atmospheric deposition rates of acidic solutes were evaluated for inclusion in the statistical models, following protocols presented in Nanus et al. (2003). The mean annual precipitation variable for each basin was derived from a 30-year (1961–1990) average annual precipitation grid (PRISM; Spatial Climate Analysis Service 2000). Average annual deposition loadings of hydrogen ion, inorganic N, and sulfate were determined by multiplying the precipitation grid with kriged chemical concentrations (Nanus et al. 2003), these deposition estimates were then calculated for each basin for inclusion in the statistical analysis. The spatial variability in solute deposition was largely controlled by precipitation amount (Nanus et al. 2003).

Model development and validation

Multivariate logistic regression was used to predict lakes with a high probability of sensitivity to atmospheric deposition for the Rocky Mountain region. Logistic regression differs from linear regression in that the result is the probability of being above or below a threshold, rather than a predicted value (Helsel and Hirsch 1992). The general linear model relates continuous dependent variables to independent variables that are either classification variables or continuous variables (SAS Institute 1990). This works well if the assumptions of linear regression are satisfied. However, with a dichotomous (binary) dependent variable, assumptions of linearity, normality of the error term, and homoscedasticity (constant variance of the error term) are violated (Menard 2002).

The logistic regression approach uses the maximum likelihood method to fit linear logistic regression models for binary response data (SAS Institute 1999). The probability (p) of being in a response category is defined by the odds ratio, the log of which transforms a variable between 0 and 1 into a continuous variable that is a linear function of the explanatory variables (Helsel and Hirsch 1992) as follows:

$$\ln\left(\frac{p}{1-p}\right) = b_0 + b_x \qquad (1)$$

where b_0 is the intercept, x is a vector of k independent variables, and b_x includes the slope coefficients for each explanatory variable. The logistic transformation is used to return the predicted values of the response variable to probability units, with the logistic regression model as follows:

$$\text{Logit}(P) = \frac{\exp(b_0 + b_x)}{1 + \exp(b_0 + b_x)} \qquad (2)$$

where Logit(P) is the probability that the ANC concentration is less than a specified ANC concentration threshold (binary response) (Helsel and Hirsch 1992).

Multivariate logistic regression models for the Rocky Mountain region were developed for sensitivity thresholds with ANC concentrations of 50 μeq/L, 100 μeq/L, and 200 μeq/L. Surface waters with ANC concentrations less than 50 μeq/L have been defined as sensitive to the effects of atmospheric deposition (Herlihy et al. 1993). ANC concentrations greater than 200 μeq/L have been defined as insensitive to acidification (Schindler 1988, Camarero et al. 1995, Sullivan et al. 2004). ANC concentrations of about 100 μeq/L provide an intermediate threshold that represents moderate sensitivity (Williams and Tonnessen 2000). For each of the three ANC thresholds, probabilities for sensitive lakes were calculated from 0–100%. For ease of presentation, the results were binned into three groups representing: 0–33% (low probability), 33–66% (medium probability), and 66–100% (high probability).

Basin-characteristic information derived from GIS was used as explanatory variables, and existing ANC concentration data ($n = 151$) were used as the dependent variables to calibrate the regression models for the identification of sensitive lakes. First, all explanatory variables were tested independently using univariate logistic regression, and the explanatory variables that have significant influence at $P \leq 0.1$ were tested in the multivariate logistic regression models. A P of ≤ 0.1 was chosen over a $P \leq 0.05$ so that more variables could be included in the multivariate analysis (Hosmer and Lemeshow 1989).

To evaluate the calibration of the logistic regression models, model-based predicted probabilities were compared to measured concentrations by using the Hosmer-Lemeshow (HL) goodness-of-fit test (Hosmer and Lemeshow 1989). A subset of lakes were not included in the calibrations so as to provide an independent data set to evaluate the calibration results. To evaluate model agreement, measured ANC concentrations were compared to predicted ANC concentrations by randomly grouping the verification lakes with measured ANC into 10 groups with an equal number of lakes. These random groupings of 10% were used to evaluate model agreement between measured and predicted ANC concentration. A higher HL value indicates a well-calibrated model (Hosmer and Lemeshow 1989). The c statistic is a measure of rank correlation of ordinal variables (SAS Institute 1990). The c statistic is normalized so that it ranges from 0 (no association) to 1 (prefect association). It is a variant of Somers' D index (SAS Institute 1990). The multivariate logistic regression model with the best statistical outcome with respect to predicting probability measured by r^2, the c statistic, and the HL goodness-of-fit test is presented for the Rocky Mountain region in *Results*.

The resulting multivariate logistic regression models were applied to all lakes greater than or equal to 1 ha. Modeling results were evaluated through samples collected from lakes in all five parks during the fall of 2004 for cross-validation of the results. The actual percentage of lakes with ANC less than 100 μeq/L was calculated for the calibration ($n = 151$) and validation ($n = 58$) set of data separately and is equal to the number of lakes with measured ANC less than 100 μeq/L divided by the total number of analyses for each 10% of decile data.

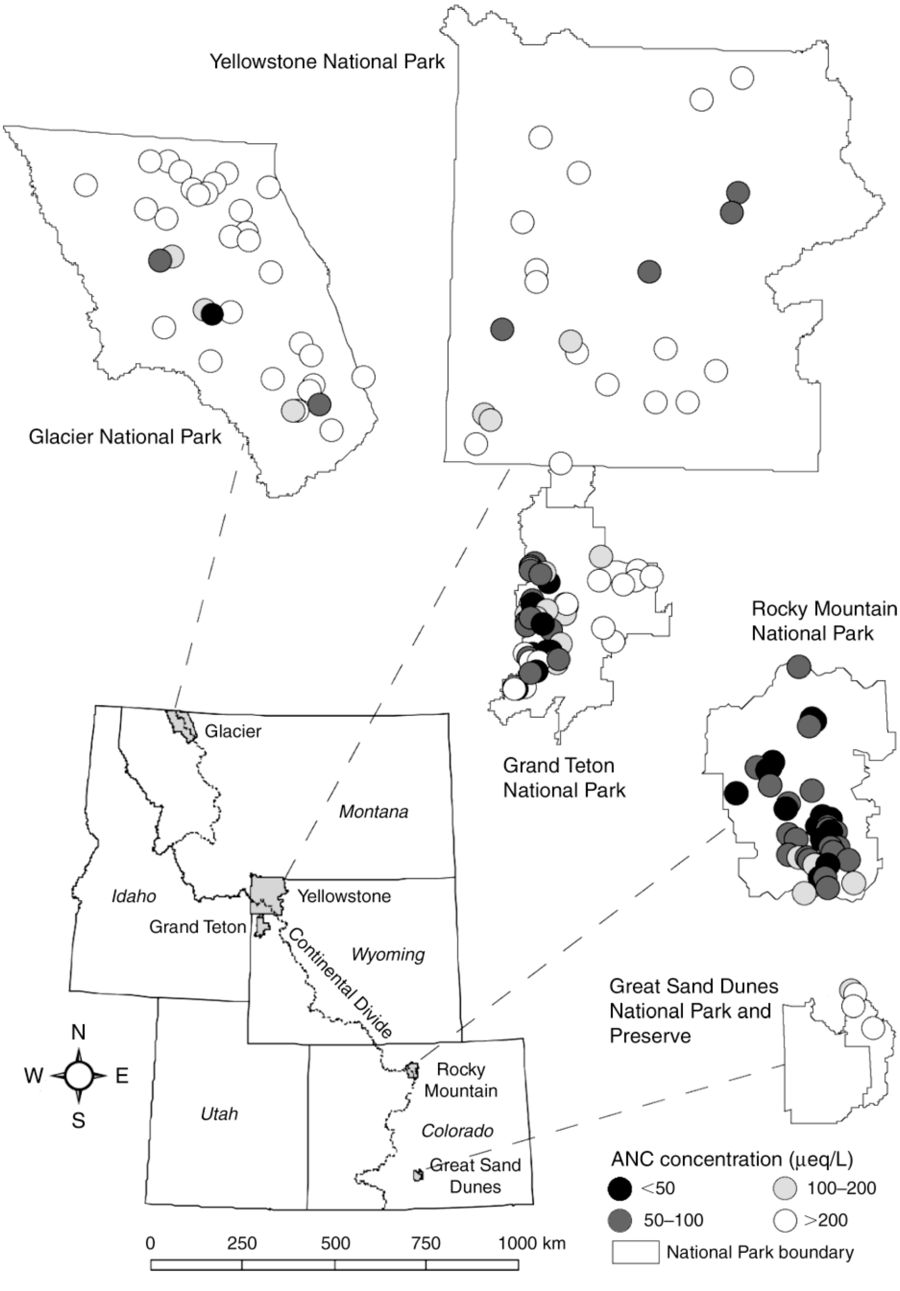

FIG. 2. ANC (acid-neutralizing capacity) concentrations from lakes used for the regional model calibration ($n = 151$) (Gulley and Parker 1985, Landers et al. 1987, Clow et al. 2002, Woods and Corbin 2003*a*, *b*, Corbin et al. 2006; K. A. Tonnessen and M. W. Williams, *personal observation*). The data are binned into four groups based on the thresholds for our ANC modeling: ANC < 50 μeq/L, 50–100 μeq/L, 100–200 μeq/L, and >200 μeq/L.

RESULTS

ANC concentrations of the 151 lakes used for model calibration ranged widely (Table 2) and differed among parks (Fig. 2). The maximum ANC concentration for Rocky Mountain was below the median concentration for Glacier and Yellowstone (Table 2). The amount of bedrock composed of low buffering capacity also varied widely among the parks (Table 2), with Rocky Mountain having the largest percentage of low-buffering-capacity bedrock. In general, lakes in parks with low ANC (Rocky Mountain, Grand Teton) were associated with large amounts of low-buffering capacity bedrock.

Concentrations of ANC were not normally distributed, with a median concentration of 122 μeq/L (Fig. 3, Table 2). Therefore, the assumptions underlying multiple linear regression, such as normal distribution, were not satisfied. Because logistic regression is used to explore the relations between binary response and a set

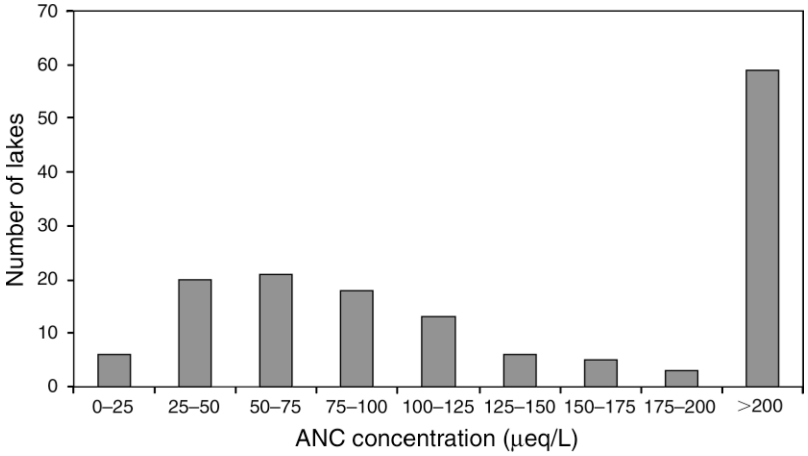

FIG. 3. Frequency of ANC concentrations for Rocky Mountain lakes in 25-μeq/L increments, used in the regional model calibration.

of explanatory variables and does not require a normal distribution, it is well suited for the ANC data.

Rocky Mountains regional lake sensitivity models

Results of the regional model calibration indicate that ANC concentrations for a threshold of less than 50 μeq/L are related to elevation and the percentage of bedrock types with low buffering capacity, including quartzite and granite (Table 3), lake basins located in Rocky Mountain and Grand Teton have these characteristics. ANC concentrations <200 μeq/L are associated with elevation, the percentage of low buffering capacity bedrock, and the ratio of lake perimeter to lake area (Table 3), lake basins in Yellowstone and Glacier do not typically have these characteristics and therefore have a low probability for ANC concentrations less than the threshold. In Glacier, where lakes have relatively high ANC concentrations (i.e., >200 μeq/L), high-buffering-capacity bedrock types are found such as carbonates and calc-silicates. About 43% of the lakes in the calibration data set have ANC concentrations <100 μeq/L (Fig. 3).

The model using an ANC concentration threshold of 100 μeq/L, representing moderate sensitivity, had the best statistical outcome based on the HL Goodness of fit and the *c* statistic (Table 3). Variables that were significantly related to ANC concentrations <100 μeq/L are elevation, percentage of basin with low-buffering-capacity bedrock, and percentage of basin with northeast aspects (Table 3) and the resultant probability equations were applied to the 769 lakes greater than 1 ha in the five national parks: $\text{Logit}(P) = (\exp[-7.4 + (0.0025 \times \text{elevation}) - (4.2 \times \%\text{basin aspect } 0\text{–}45^\circ) + (1.6 \times \%\text{basin with low buffering capacity bedrock})])/(1 + \exp[-7.4 + (0.0025 \times \text{elevation}) - (4.2 \times \%\text{basin aspect } 0\text{–}45^\circ) + (1.6 \times \%\text{basin with low buffering capacity bedrock})])$, where Logit($P$) is defined as for Eq. 2.

Results of the regional model indicate that 53% of lakes in Rocky, Great Sand Dunes, and Grand Teton had a high probability (66–100%) for lake ANC concentrations less than 100 μeq/L (Fig. 4). Few lakes in Glacier and Yellowstone had a high probability for ANC concentrations less than 100 μeq/L (Fig. 4). The lakes that had a high probability of having an ANC

TABLE 3. Results of multivariate logistic regression analyses ($n = 151$), logistic regression coefficients, and P values.

Multivariate model and explanatory variable	Range	Median	Coefficient	*P*	HL goodness of fit (r^2)	*c* statistic
Regional_50 (ANC threshold = 50 μeq/L)						
Elevation at lake outlet (m)	956–3774	2577	0.001	0.06	0.92	0.86
Bedrock geology with low buffering capacity (%)	0–100	97	8.01	0.02		
Regional_100 (ANC threshold = 100 μeq/L)						
Elevation at lake outlet (m)	956–3774	2577	0.003	<0.001	0.98	0.90
Bedrock geology with low buffering capacity (%)	0–100	62	1.65	0.04		
Northeast aspect (%)	0–100	17	−4.15	0.08		
Regional_200 (ANC threshold = 200 μeq/L)						
Elevation at lake outlet (m)	956–3774	2577	0.001	0.004	0.96	0.90
Bedrock geology with low buffering capacity (%)	0–100	62	3.06	<0.001		
Ratio of lake perimeter to area (%)	0–100	5	−9.15	0.04		

Note: The *c* statistic is a measure of rank correlation of ordinal variables, normalized so that it ranges from 0 (no association) to 1 (perfect association).

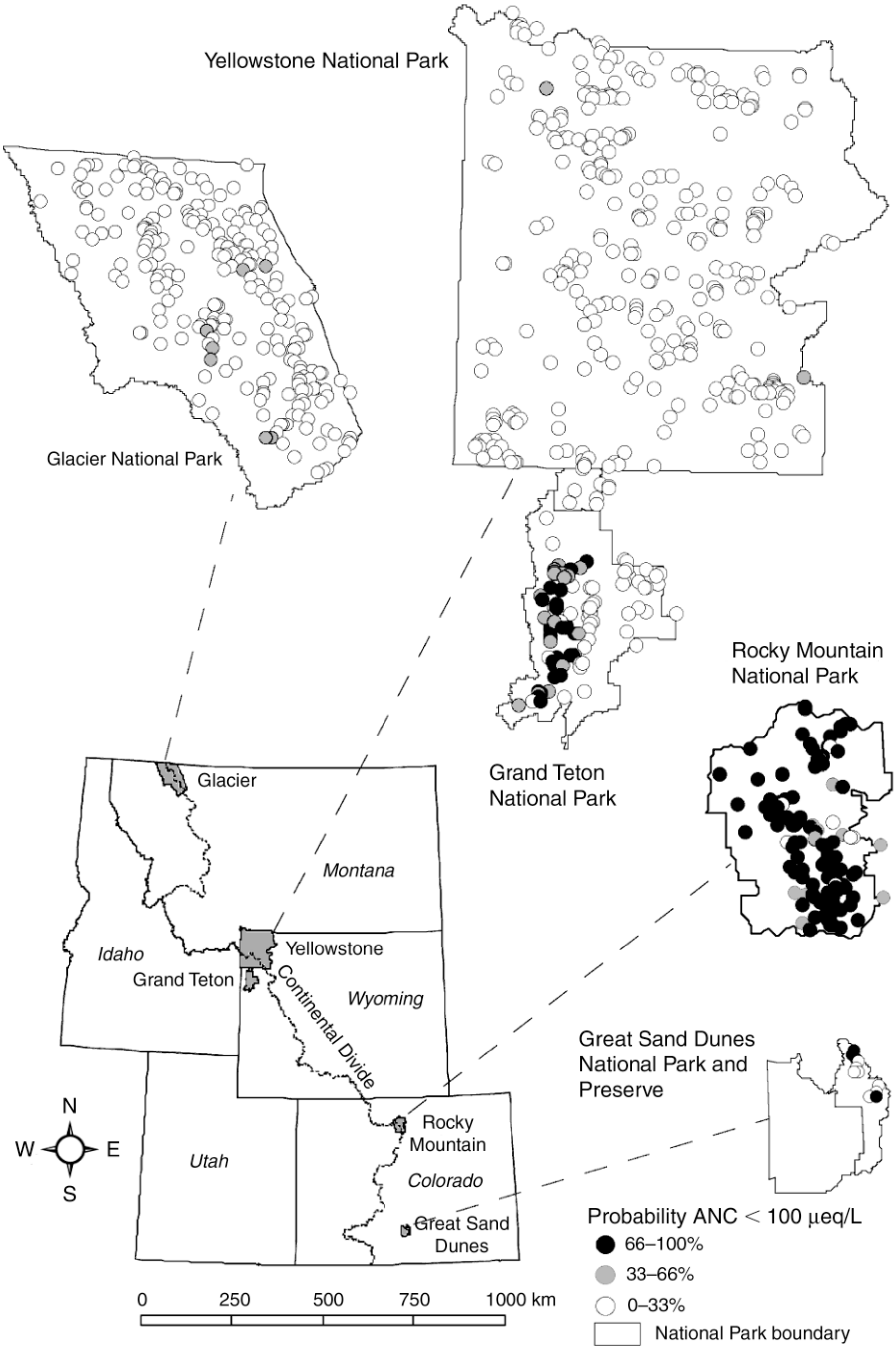

FIG. 4. Probability of lake ANC concentrations <100 µeq/L in five Rocky Mountain National Parks. All probabilities ranging from 0% to 100% were evaluated; the data are binned into three groups for ease of presentation.

concentration less than 100 µeq/L in the regional model are located at elevations above 3000 m, with less than 30% of the basin with northeast aspect, and greater than 80% of the basin with bedrock of low buffering capacity (i.e., quartzite, granite, gneiss, and schist).

Modeling results were cross-validated from 58 additional lakes sampled during 2004. The spatial distribution of ANC concentrations (Figs. 5 and 6) indicate that ANC concentrations are lowest (more sensitive to deposition of atmospheric contaminants) in Rocky Mountain and Grand Teton and highest (less sensitive to deposition of atmospheric contaminants) in Glacier and Yellowstone, similar to the calibration data set.

Predicted probabilities for ANC concentrations less than 100 µeq/L were compared with measured ANC concentrations to evaluate predictive ability for the

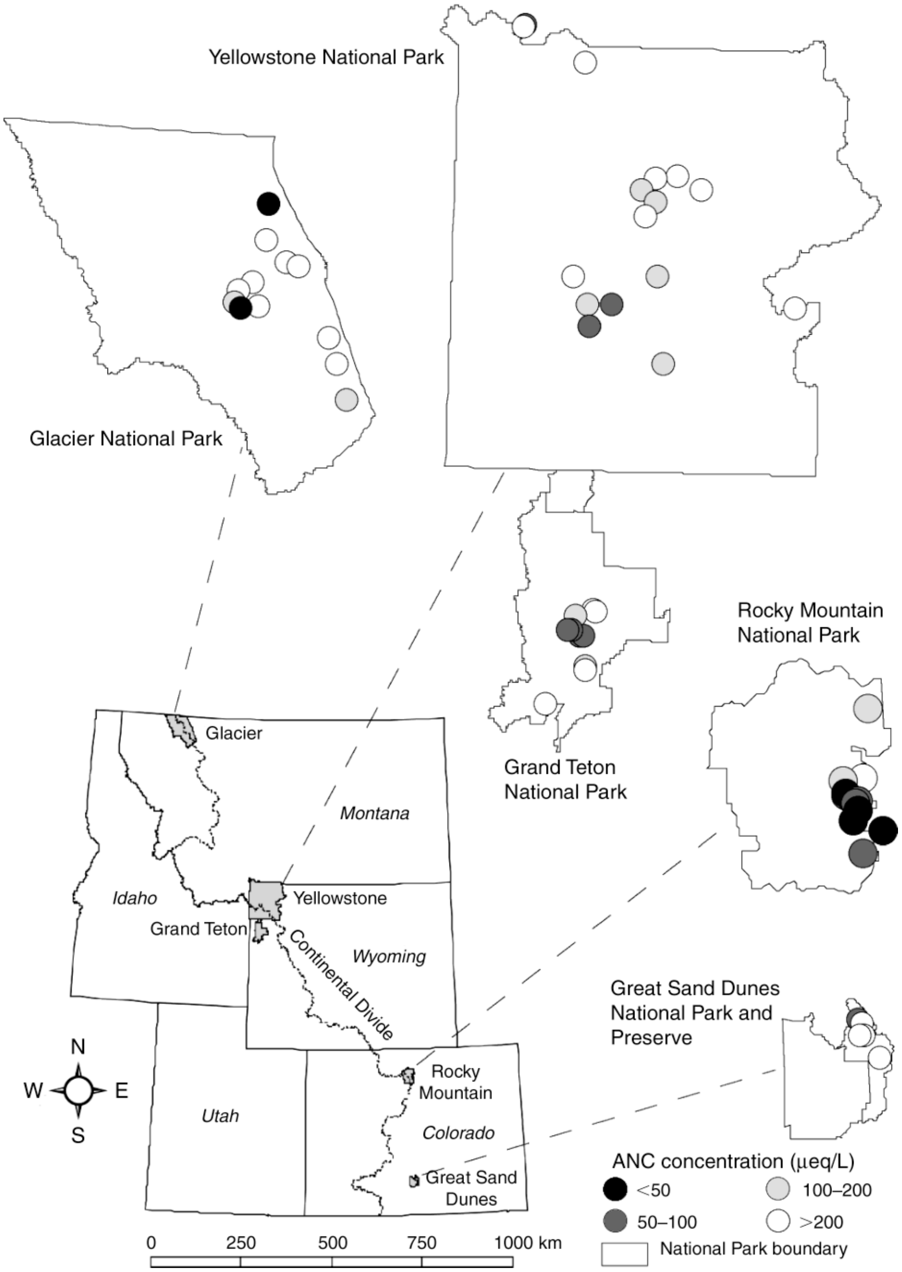

FIG. 5. ANC concentrations from lakes used for validation of the regional model, binned into four groups based on the thresholds for our ANC modeling ($n = 58$ lakes).

Rocky Mountain regional model. ANC concentrations from the measured lakes were converted to binary classification of 1 for ANC concentrations <100 µeq/L and 0 for ANC concentrations >100 µeq/L. The conversion to binary classification enabled a direct comparison between the percentage of measured ANC concentrations and the average predicted probability within each 10% decile of the data. For the calibration data set ($n = 151$), the r^2 value is 0.98 for lakes with a predicted probability less than 100 µeq/L compared with actual percentage of lakes with ANC concentrations less than 100 µeq/L (Fig. 7). For the validation data set ($n = 58$), the r^2 value is 0.93, very similar to the calibration value of 0.98 (Fig. 8).

DISCUSSION

The combined use of GIS modeling and multivariate logistic regression using available GIS and water-quality data made regional-scale predictions that passed rigorous field validation. This approach was validated with independent water-quality data collected at 58 lakes during base flow in 2004. The high r^2 (0.93) in the

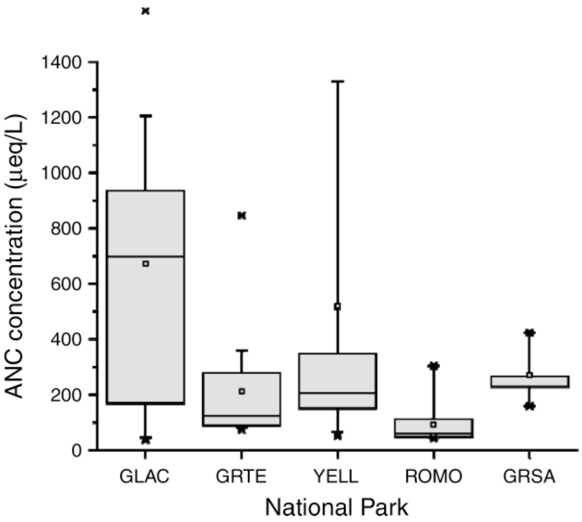

FIG. 6. Box plot showing distribution of concentrations measured at 58 lakes during fall 2004. National Park abbreviations are: GLAC, Glacier; GRTE, Grand Teton; YELL, Yellowstone; ROMO, Rocky Mountain; GRSA, Great Sand Dunes. The plots show whisker range (5–95%) and box range (25–75%) with median value; squares are the mean, and asterisks are outliers.

regional model using the 2004 validation data indicates that the model can successfully identify a subset of lakes in national parks of the Rocky Mountains that are most likely to be sensitive to acidic deposition. The approach presented in this paper may be transferable to other remote high-elevation protected areas that are sensitive to atmospheric deposition of contaminants, such as wilderness areas in national forests in the western United States.

Relations between ANC and basin characteristics

Lakes across the region were identified as sensitive based on a high predicted probability of having an ANC concentration of less than a specified threshold (50 μeq/L, 100 μeq/L, and 200 μeq/L; Fig. 5). These results support the initial hypothesis that in the Rocky Mountains, ANC is low (<100 μeq/L) in lakes that are in moderate to high-elevation headwater basins, with little soil cover, and low-buffering capacity bedrock. This hypothesis is in agreement with previous work conducted in the Rocky Mountains (Clow and Sueker 2000, Rutkowski et al. 2001). Of the basin characteristics that were considered in the regional model, elevation and bedrock geology were found to have the greatest effect on predicted ANC concentration probabilities (Table 3).

Elevation was found to be a predictor of lake ANC, such that ANC was inversely correlated with elevation, consistent with Rutkowski et al. (2001). However, Berg et al. (2005) did not find elevation to be a significant predictor of ANC concentration in the Sierra Nevada. In the Rocky Mountains, physical characteristics of high-elevation basins, combined with the storage and release of contaminants in snowmelt runoff from deep snowpacks, make them susceptible to atmospheric contamination (Williams et al. 1996, Baron and Campbell 1997, Clow and Sueker 2000). Results of this study indicate that for the Rocky Mountain regional model, increased elevation at the lake outlet was significantly related to low ANC concentrations (<100 μeq/L). For the Rocky Mountain regional model, significant relations were found between ANC concentrations and bedrock types. These results of bedrock geology are consistent with findings of Clow and Sueker (2000) in Rocky and Corbin et al. (2006) in Grand Teton.

Atmospheric deposition of hydrogen ion, inorganic N, and sulfate has the potential to alter the chemistry of aquatic ecosystems through nitrogen saturation and episodic acidification, thus increasing the sensitivity of lakes to future changes related to atmospheric deposition. Deposition estimates were calculated for each basin and were included in the analysis for the region. Results, however, indicated that deposition was not statistically significantly related to ANC concentration and, therefore, it was not included in the final equations. This result may be because deposition is fairly similar among sites within each park (Nanus et al. 2003), due to the resolution of PRISM precipitation maps used to develop deposition estimates. It may also be due to the fact that

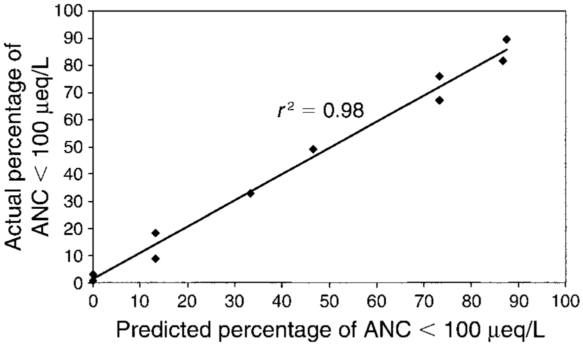

FIG. 7. Percentage of actual ANC concentrations <100 μeq/L and the predicted probability of ANC concentrations <100 μeq/L (calibration data, $n = 151$ lakes).

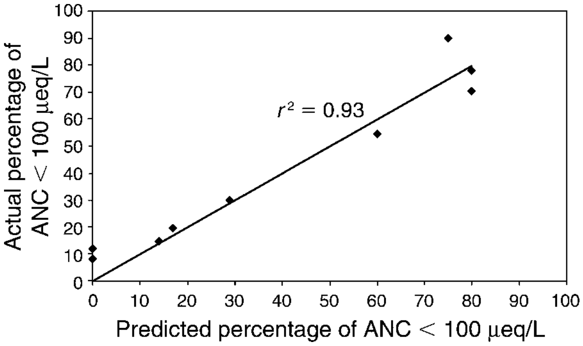

FIG. 8. Percentage of actual ANC concentrations <100 μeq/L and the predicted probability of ANC concentrations <100 μeq/L (validation data, $n = 58$ lakes).

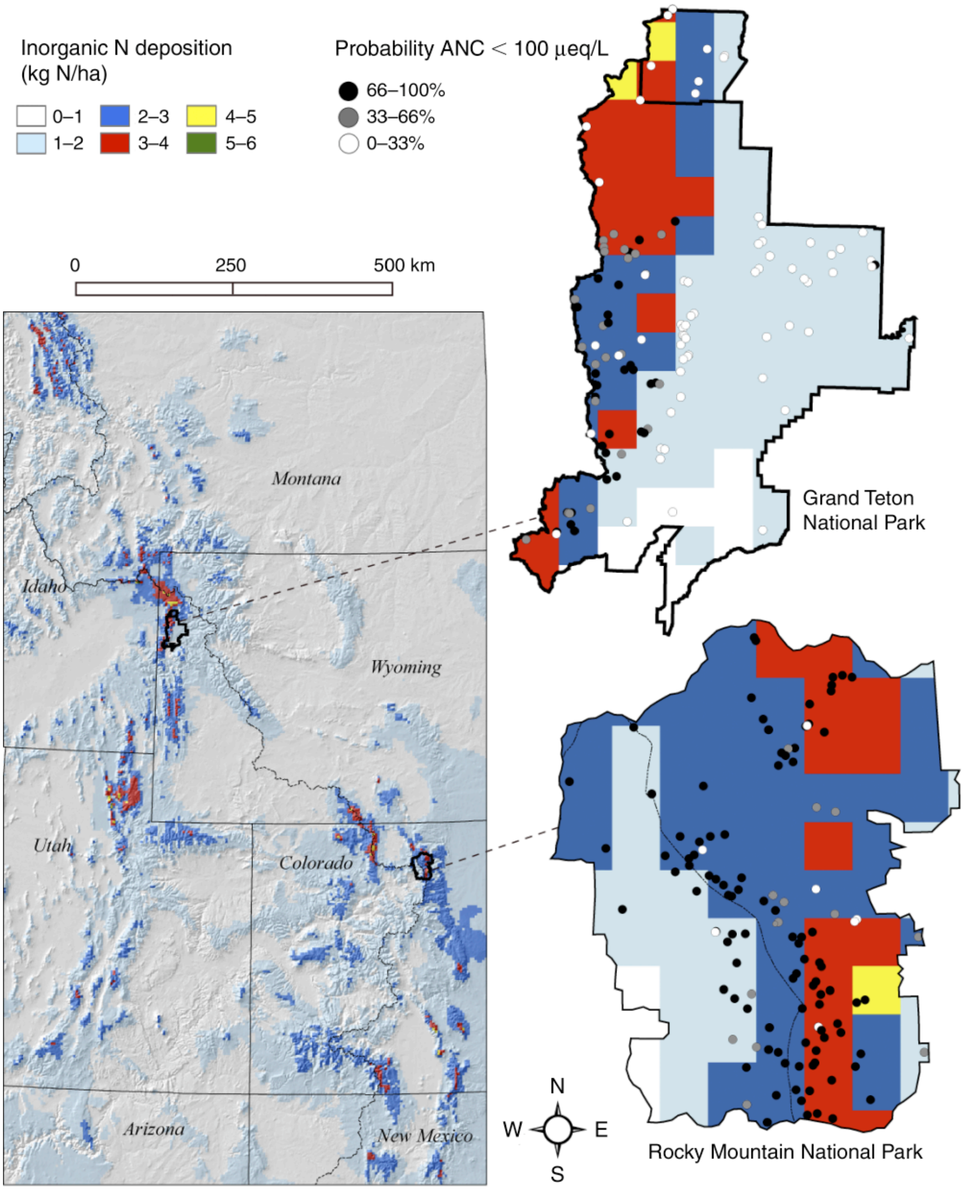

FIG. 9. Average annual inorganic N deposition in the Rocky Mountains (Nanus et al. 2003) overlaid with the probability for lake sensitivity in Grand Teton and Rocky Mountain National Parks.

acidic deposition in the western United States is not sufficient to cause chronic acidification.

Management applications

Deposition estimates and lake sensitivity maps can be used together by resource managers to identify lakes that have both a high probability for sensitivity to atmospheric deposition and a relatively high deposition of acidic solutes. Average annual atmospheric deposition estimates were overlaid with the results of the sensitivity analysis to locate these lakes. In Grand Teton and Rocky, 53% of lakes are sensitive to the deposition of acidic solutes and areas within these parks have high rates of inorganic N, sulfate, and acid deposition (Nanus et al. 2003). In the Colorado Rockies, researchers have shown that elevated levels of N deposition have caused changes in aquatic ecosystems at high-elevations (Williams et al. 1996, Baron 2006). Therefore, there is considerable interest in identifying areas in Grand Teton and Rocky that have both sensitive lakes and high inorganic N deposition as shown in Fig. 9. In Grand Teton and Rocky, lakes with a high probability (66–100%) for ANC < 100 µeq/L are primarily located in areas that receive 2–5 $\mathrm{kg \cdot ha^{-1} \cdot yr^{-1}}$ inorganic N. In Grand Teton, lakes with a low probability (0–33%) are located in areas that receive less than 2 $\mathrm{kg \cdot ha^{-1} \cdot yr^{-1}}$ inorganic N. This is an example of an application for resource managers using these maps to find lakes most at risk to change due to acidic atmospheric deposition.

The GIS and logistic regression modeling approach can be used as a cost-effective tool to help resource managers. In the future, the probability estimates can be used to select lakes to be included in a monitoring program. For Grand Teton and Rocky Mountain, where lakes appear to be most sensitive to acidic deposition, long-term monitoring programs are needed in order to capture seasonal variability and potential episodic acidification. This analysis predicts the probability of ANC concentrations below a set threshold, but does not include other chemical constituents. Nitrate and sulfate concentrations may be evaluated using a similar approach to identify significant relations between basin characteristics and lake chemical concentrations in select national parks of the western United States. Future sampling sites also could include climate stations for precipitation sample collection that would allow resource managers to observe short-term and long-term variability in inorganic N and sulfate wet deposition.

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